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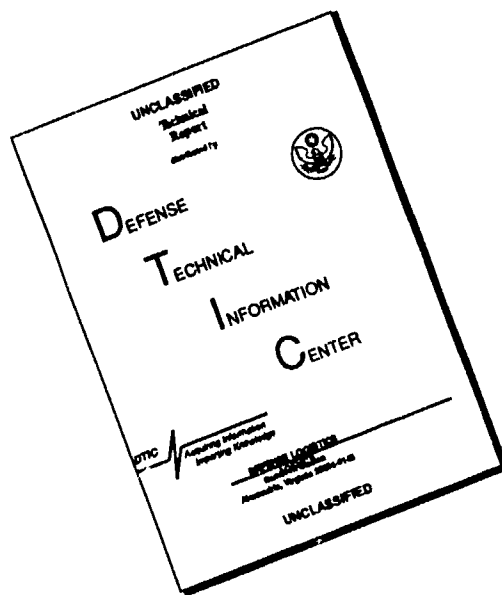
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NAVWEPS REPORT 7630
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COPY 14

EVALUATION OF PROPELLANT DEFECTS USING TRANSPARENT ROCKET MOTORS

By

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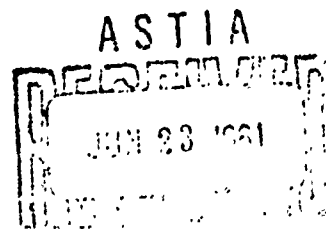
ABSTRACT. A transparent motor tube loaded with solid propellant has proved useful as a tool for studying problems of motor operation. Forty transparent motors were fired in a test program for the purpose of evaluating improper case bonding, cracked grains, and igniter operation. Conditions under which side burning occurs in improperly case-bonded motors were determined, and the rate of side burning in 2- and 5-inch motors was calculated. The ignition process and the performance of an igniter were observed, using a transparent half-motor. High-speed film records of side burning and cracked-grain burning were obtained, and 100-pps binary-coded timing (BCT) was used to obtain accurate correlation of pressure, thrust, and film records

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U.S. NAVAL ORDNANCE TEST STATION

China Lake, California

March 1961

U. S. NAVAL ORDNANCE TEST STATION

AN ACTIVITY OF THE BUREAU OF NAVAL WEAPONS

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FOREWORD

This report presents the results of a study, conducted at the U. S. Naval Ordnance Test Station during 1959-1960 as part of an applied-research program, to determine the effect of grain defects on the internal ballistics of small solid-propellant rockets as observed using transparent motors made of Lucite.

This study was supported by Task Assignment RMMP-22-038/216-1/F-009-06-002.

The report was reviewed for technical accuracy by Frank G. Crescenzo and Charles W. Bernard.

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NEGATIVE NUMBERS OF ILLUSTRATIONS

Fig. 1, LHL L049211; Fig. 2, LHL L059050;
Fig. 3, LHL L061803; Fig. 4, LHL L059049;
Fig. 5, LHL L059949; Fig. 6, LHL L049862;
Fig. 7-16 , none.

INTRODUCTION

The physical integrity or soundness of a solid-propellant grain is a major factor affecting the performance of a rocket motor. Imperfections such as cracks in the propellant or the existence of extra uninhibited propellant surface usually causes changes in the desired internal ballistics, which may result in catastrophic failure of the rocket motor. The lack of an effective tool to correlate accurately motor performance with motor defects has hampered serious study of the problem. The work described here was undertaken to evaluate systematically the performance of several static-test motors that contained propellant and case-bonding imperfections. Data obtained from these firings were then compared with data obtained from firings of motors containing normal grains. The performance of each motor was evaluated from pressure and thrust data and by high-speed motion pictures. Lucite tubes were used as motor chambers in the fabrication of all motors. This allowed the direct observation of such phenomena as side burning, hot-spot formation, and the burning pattern of cracked propellant grains. The qualitative data were correlated with pressure and thrust data by using 100-pps binary-coded timing (BCT). In this manner, the various causes for abnormal motor behavior were isolated and analyzed.

A transparent motor containing a grain half of which was inert (called a half-motor) made it possible to observe the propellant surface during the ignition. In this manner, the performances of bag and hot-wire igniters were studied and compared under conditions of pressure and internal grain geometry that one usually finds in a practical rocket motor.

The analysis did not include the possible effects of erosive burning and combustion instability caused by high-frequency pressure oscillations within the propellant cavity during motor operation. Because of the low length-to-diameter ratio, the gas velocity gradient along the length of the motor should be small, and erosive burning effects can be ignored. Also, investigations showed that aluminized propellants such as the one used in this program do not exhibit instability occasioned by oscillatory combustion.¹ It was therefore assumed that the over-all behavior of all the test motors of this program was attributable to the presence or absence of defects in the propellant grains.

¹ U. S. Naval Ordnance Test Station. Combustion Instability (U), by E. W. Price. China Lake, Calif., NOTS, February 1960. 24 pp. (Technical Article 3, NOTS TP 2400), CONFIDENTIAL.

The primary objectives of the program were

1. To study the effect of liner-propellant separation on the performance of 2- and 5-inch test motors
2. To study the effect of propellant cracks on the ballistic performance of 2- and 5-inch motors
3. To test the feasibility of using a transparent half-motor to study igniter performance and ignition problems

TEST PROGRAM

FABRICATION OF TRANSPARENT TEST MOTORS

The 40 test motors used in this program were fabricated using motor chambers made of Lucite. Lucite was selected because of its good optical properties and high strength. The reported tensile strength for this material is 7,000 psi at 75°F, and this was the value used in designing the motor tube. All tubes were designed to contain a maximum internal pressure of 4,000 psi. Tubes for the 2-inch motors were 10 3/4 inches long, with inside and outside diameters of 1 13/16 and 4 inches, respectively. The corresponding dimensions of the 5-inch motors were 10 3/4, 5, and 10 inches. As a first step in motor fabrication, all tubes were lined with a polyurethane rubber approximately 0.065 inch thick. This was done by pouring uncured liner material in the tube and spinning the latter on a lathe until the material had cured. The curing time was 6 hours at a room temperature of approximately 80°F. It was found early in the program that the liner provided adequate protection for the walls of the tubes. After a given firing, the liner was removed from the tubes, which were relined later and used again. The following materials were used for liner compositions:

	Wt., %
Castor oil (DB grade)	76.8
2,4 Tolyene diisocyanate	23.0
Ferric acetyl acetate (FEAA)	0.2
Total	100.0

The physical properties, at 77°F, comprised the following:

Ultimate tensile strength, psi	234
Ultimate elongation, %	62
Hardness (Shore A)	43
Elastic modulus, psi	439

Control motors containing no propellant defects were cast with a slurry of high-energy Nitrasol propellant around a mandrel that had been previously positioned in a lined motor tube. After the propellant was cured by oven heating, the mandrel was removed leaving a grain

with the desired internal configuration. An eight-point-star design was used for the 2-inch motors, and a six-square-point design was used for the 5-inch motors. The selection of these two internal grain configurations was purely arbitrary.

A disassembled 2-inch motor is shown in Fig. 1. The steel plate on the right side of the picture holds the graphite nozzle insert; the steel plate on the left side holds the pressure tap. The assembly is held together by four 1-inch bolts shown in the background.

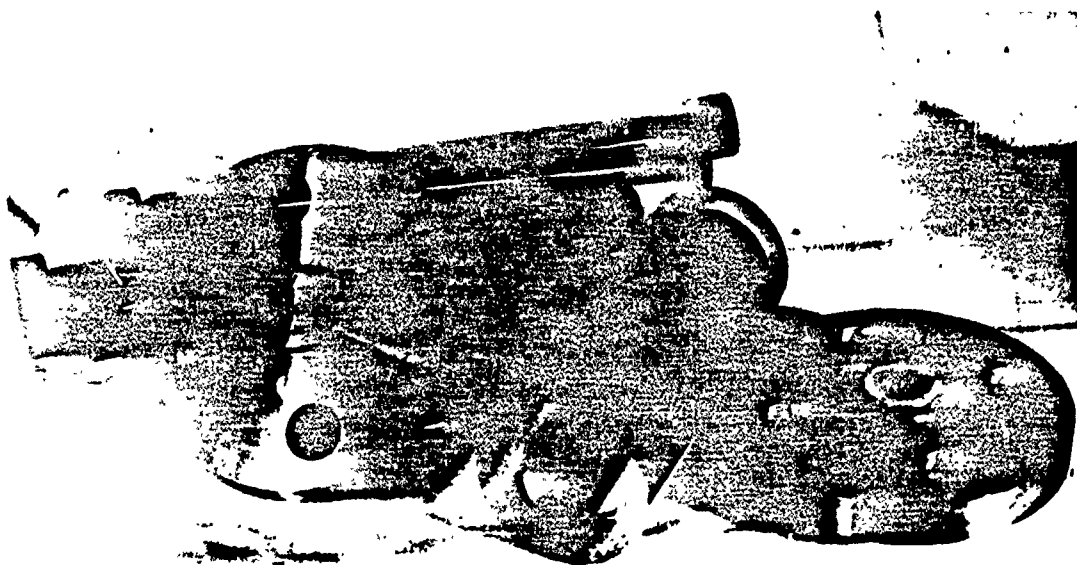


FIG. 1. Parts for Transparent, 2-Inch, Solid-Propellant Static-Test Motor.

All motors were fired using a bag igniter that contained a mixture of aluminum pellets and finely divided magnesium Teflon actuated by a high-resistance (hot) wire. The 8-gram igniter weight was kept constant throughout the program except for those igniters used in ignition studies. This was done to minimize the variation in ignition energy supplied to each motor. It was assumed, therefore, that any variation in response during ignition between motors was due to the presence of defects. Physical properties, at 77°F, comprised the following:

Ultimate tensile strength, psi . . .	200
Elongation at rupture, %	100
Hardness (Shore A)	80

The ballistic properties were as follows:

Burning rate	
Coated oxidizer, in/sec	0.34
Uncoated oxidizer, in/sec	0.50
Pressure exponent	0.60
Temperature coefficient, %/°F	0.35

Certain defects were built into some motors by a modification of the fabrication method described above. Liner-propellant separation was achieved by placing a brass shim in contact with the liner surface before casting the propellant. The shims were coated with silicone rubber RTV 60 to promote easy removal from the motor. Shim thicknesses were varied according to the design of the experiment. After the propellant was cast and cured, the shim was removed leaving a portion of the propellant surface adjacent to the liner uninhibited and separated. V-shaped slots machined in some of the motors were positioned so that the uninhibited or separated area was connected by a channel, which permitted possible gas flow to this area from the main internal cavity of the motor. This configuration and its modifications are shown in Fig. 2 and are identified as Cases I, II, and III.

The second motor defect fabricated (Fig. 3) was a simulated crack in the propellant grain. This was achieved by placing a silicone-coated

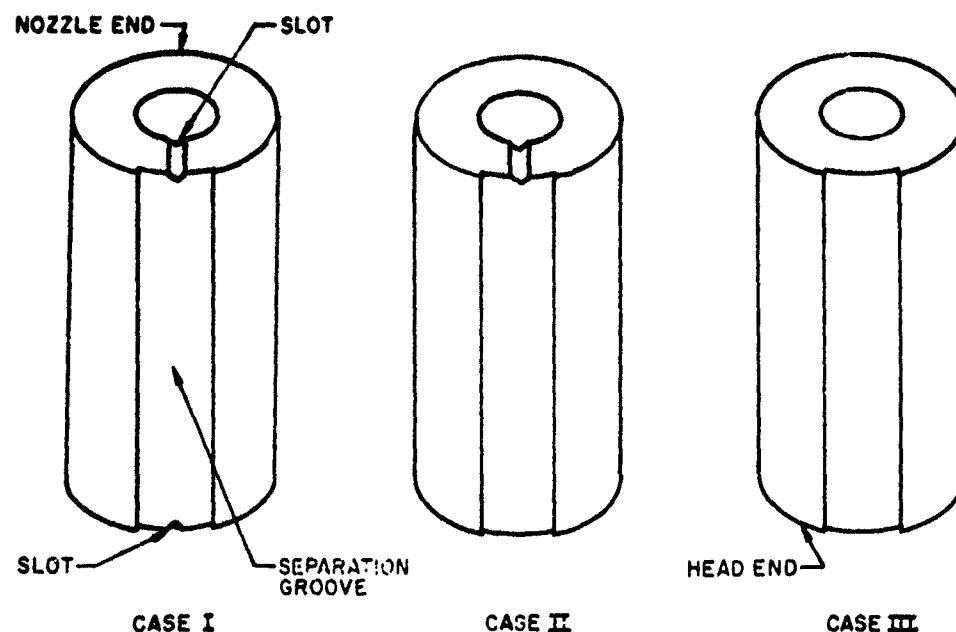


FIG. 2. Configuration of Motor Defects.

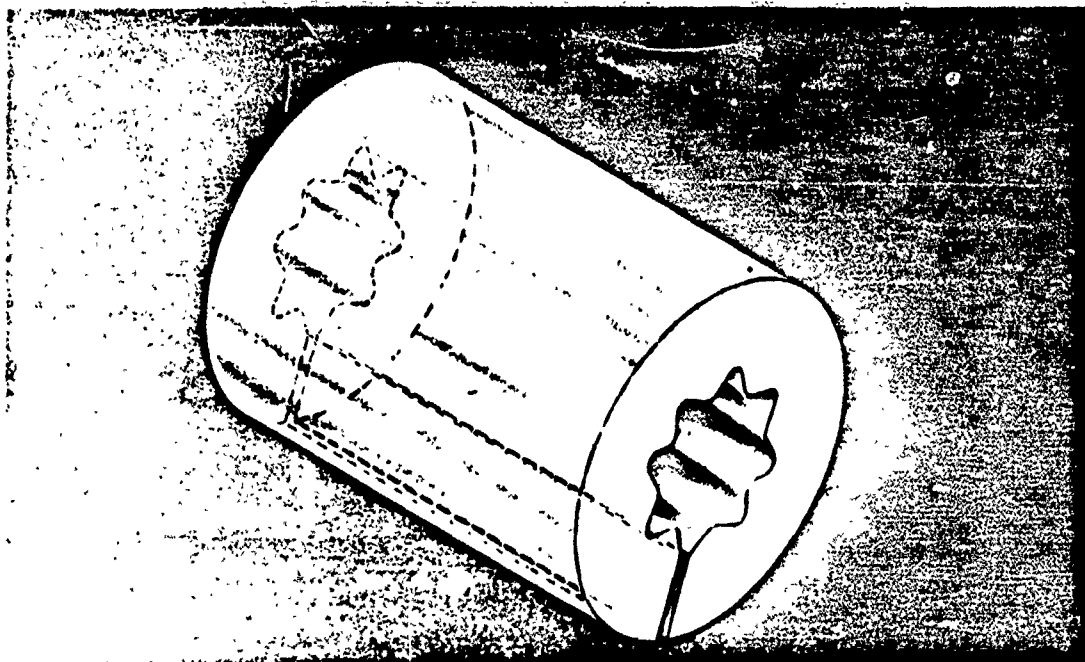


FIG. 3. Configuration of Cracked Grain.

metal shim parallel with the mandrel so that it extended from the tip of a star point perpendicularly to the surface of the liner. This strip of metal was removed after curing of the propellant. The position of the crack was chosen to conform to the point of maximum stress in a normal grain under internal pressure. The grain would most probably crack at this position because of thermal stresses during severe temperature cycling. The shim thickness used was 0.010 inch, and the actual measured crack sizes varied between 0.010 and 0.014 inch.

A third type of grain used in this program (Fig. 4) permits observation during ignition of the propellant. The grain was made by casting half of the motor with the mandrel in position, with polyurethane resin R-1. After the inert material cured, the remaining volume of the motor was filled with propellant.

INSTRUMENTATION

The output from pressure and thrust gages connected to the motors was recorded on a galvanometer oscillograph operating at 36 in/sec. In addition, qualitative data on motor performance were recorded by high-speed cameras. Fastax and Photo-sonic cameras photographed the test runs simultaneously at 7,000, 4,000, and 2,000 frames per second.

Accurate correlation or matching of qualitative data with pressure and thrust data was achieved by using 100-pps BCT. Coded timing eliminates the requirement that cameras run at constant speed and that a fixed zero time be established before the start of an event. Timing

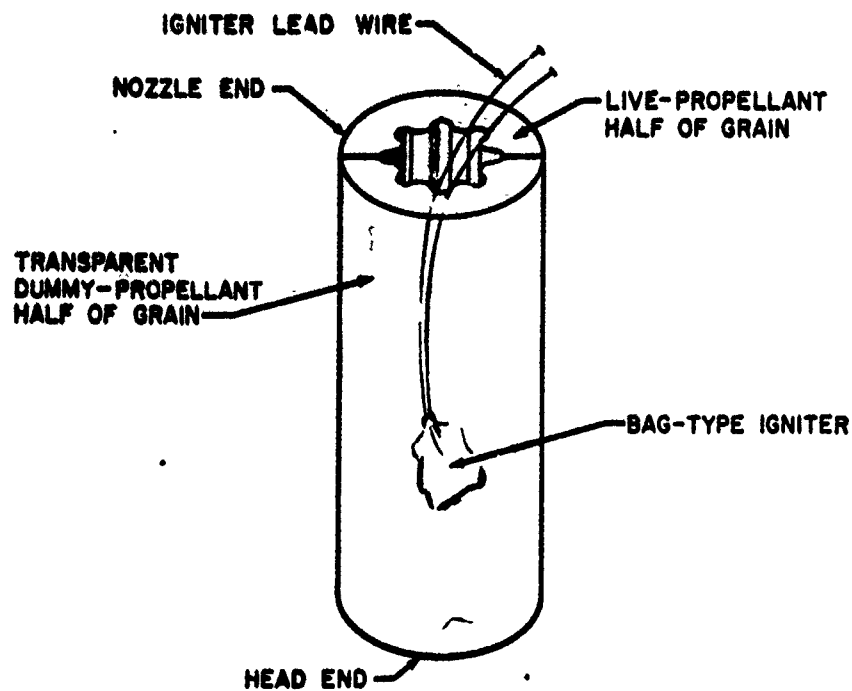


FIG. 4. Half-Motor Grain Design for Ignition Study.

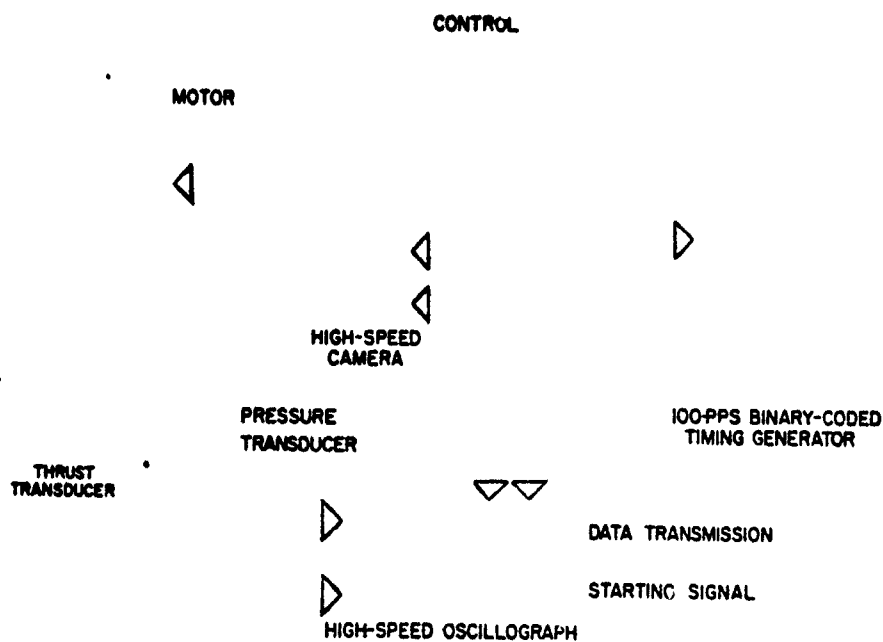


FIG. 5. Instrumentation Arrangement for Tests of Transparent Motors.

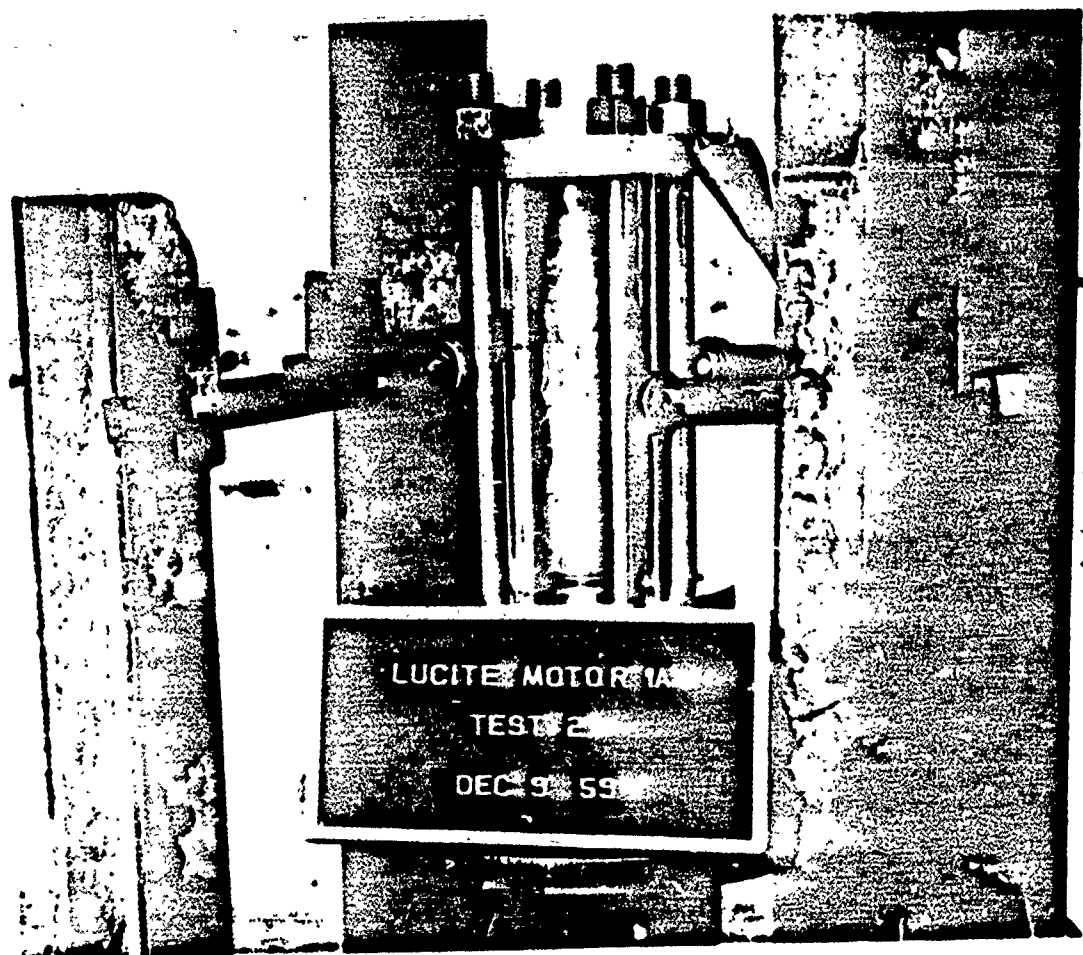


FIG. 6. Transparent 2-Inch Motor on Test Stand.

signals from the timing generator were sent to the recording oscillograph and to neon lamps mounted inside the cameras. By comparing timing lines that appeared both on the oscillograph and on the motion picture record, film frames could be matched with a point on the pressure and thrust records. Observed phenomena associated with motor operation were thereby correlated with motor pressure and thrust. The 100-pps BCT unit developed at NOTS² provided a binary display at elapsed time every 0.1 second for 51.1 seconds. To ensure accurate counting between intervals of the coded signals, pulses of 1 kc were injected into the coded signals. A block diagram of the instrumentation arrangement is shown in Fig. 5, and the actual motor in the test stand is shown in Fig. 6.

² U. S. Naval Ordnance Test Station. Instructions for 100-PPS Binary-Coded Timing (BCT) Equipment, by C. A. Mauss. China Lake, Calif., NOTS, June 1955. 39 pp. (NOTS 1457).

LINER-PROPELLANT SEPARATION EXPERIMENT

This experiment was conducted in an effort to study the behavior of test motors containing known amounts of liner-propellant separation, and to determine the conditions under which side burning would occur. The design and test data of this experiment are shown in Table 1. Each of the 2-inch motors, with the exception of motor No. 4, contained a surface section of propellant that was separated from the liner. Three motors had the configuration shown in Case I, 3 had that shown in Case II, and 3 had that shown in Case III (Fig. 2). All 10 were fired at ambient temperatures ($75 \pm 5^\circ\text{F}$).

TABLE 1. LINER-PROPELLANT SEPARATION EXPERIMENT

Description					Firing data			
Motor no.	Shim thickness, in.	Separation, in.		Case	Ignition delay, ms ($\sigma = 11.2$)	Burning time, sec ($\sigma = 0.035$)	Integral, psi-sec	Impulse, lb-sec
		Nozzle	Head end					
1	0.020	0.033	0.037	III	190	0.860	690	220
2	.005	.008	.009	I	196	.782	696	233
3	.005	.008	.008	III	184	.847	688	221
4 ^a	186	.915	706	227
5	.010	.020	.010	II	193	.855	646	214
6	.005	.008	.005	II	175	.875	688	226
7	.010	.010	.015	III	198	.876	692	224
8	.020	.037	.043	I	188	.872	702	240
9	.010	.015	.008	I	199	.907	680	215
10	0.020	0.045	0.045	II	218	0.899	638	213

^aControl round.

The pressure-time curves are shown in Fig. 7 through 10. Figure 7 shows that the pressure-time history of the control motor is progressive. The internal configuration of the grain causes the burning-surface area to increase until web burnout. Test results are useful, however, since the curves for the abnormal cases were compared with that for the control round. Differences in total impulse of motors are caused by differences in propellant weight.

Results show that abnormal curves were obtained only from motors containing Case I defects. Motors No. 2, 8, and 9 show secondary pressure peaks occurring during various stages of motor operation. The peak for motor No. 2 occurred during the initial stages of burning, and the peak for motor No. 9 occurred during the latter stages. Film records were not obtained for motors 2 and 8 because of camera failures. The film record for motor 9, however, proved that the existence of the peak shown on the pressure record was due to side burning at the liner-propellant interface. This phenomenon was observed directly through the walls of the Lucite motor tube. Figure 11 is a picture sequence of

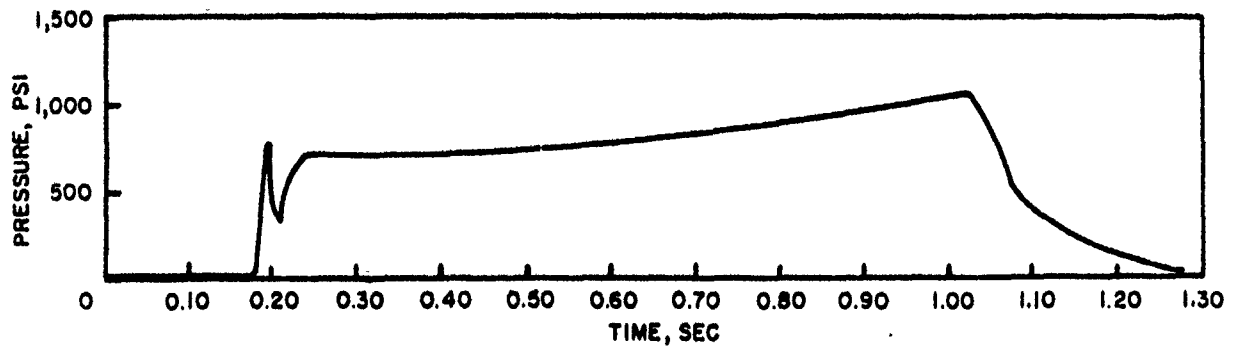


FIG. 7. Pressure-Time Curve, 2-Inch Control Motor No. 4.

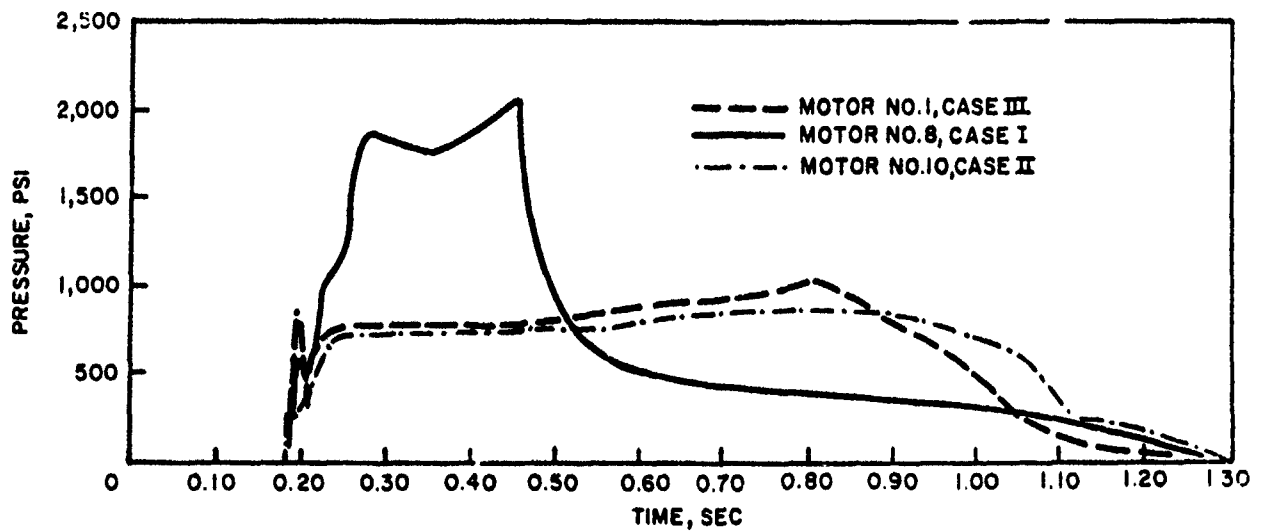


FIG. 8. Pressure-Time Curves, 2-Inch Motors No. 1, 8, and 10.

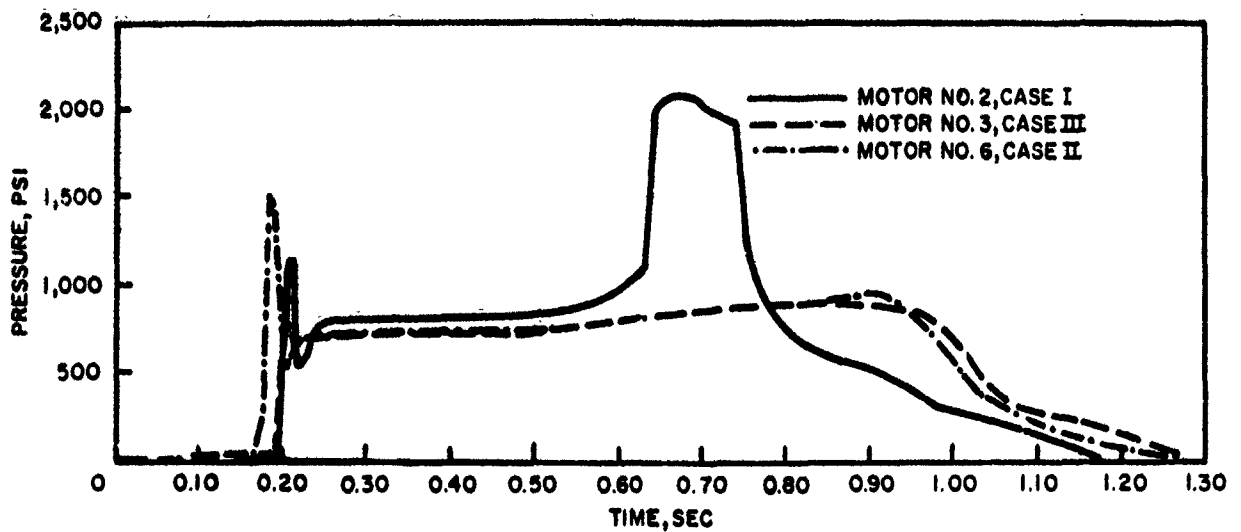


FIG. 9. Pressure-Time Curves, 2-Inch Motors No. 2, 3, and 6.

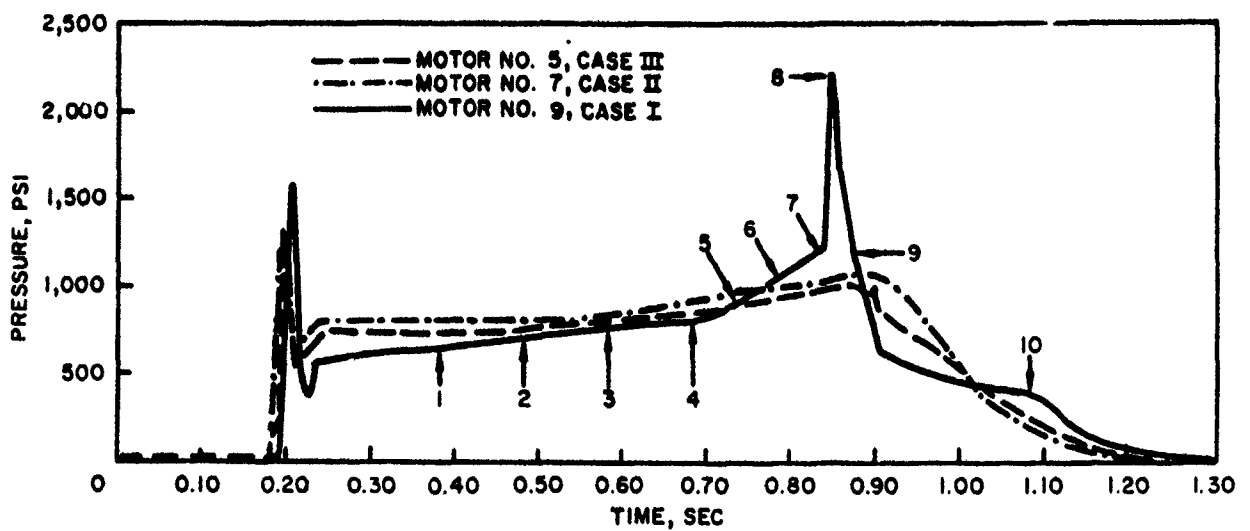


FIG. 10. Pressure-Time Curves, 2-Inch Motors No. 5, 7, and 9.

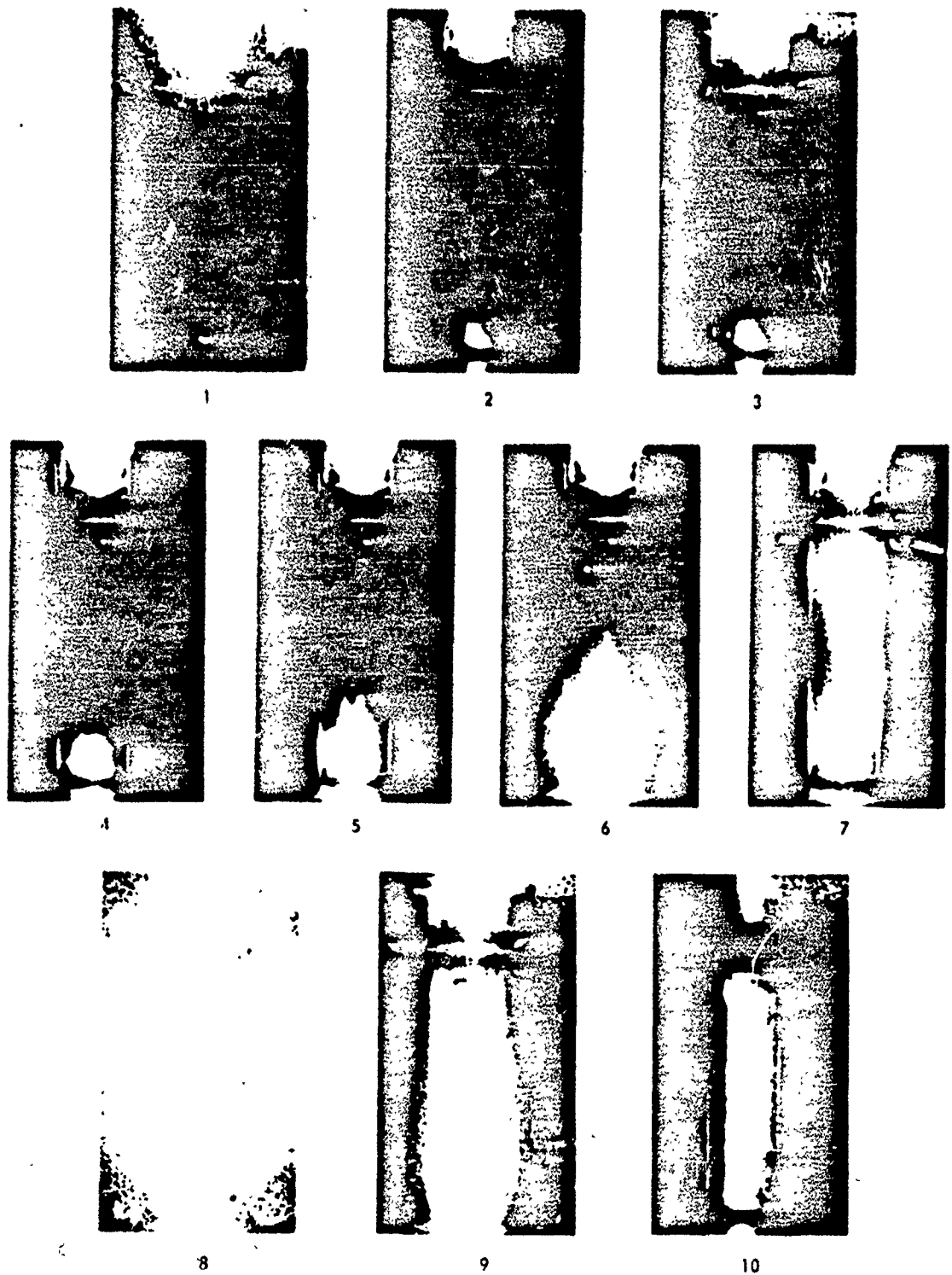


FIG. 11. Side Burning in 2-Inch Motor No. 9. Numbers correspond to numbered points in Fig. 10.

motor 9 during operation. Each picture was matched to a point on the pressure-time curve for this motor (Fig. 10). The numbers 1 to 10 on the curve in Fig. 10 correspond to the views 1 to 10 in Fig. 11. From these data it was concluded that the peaks for motors 2 and 8 were also caused by side burning.

In relating these results with the configuration of the defect and the separation distance, it may be concluded that side burning occurs only when slots are provided on both ends of the grain. The slot on the head end of the grain provides a gas flow channel through which the combustion products flow and ignite the exposed propellant in the separation groove. The combustion products then flow across the fresh propellant surface and, by convective heat transfer, raise the temperature of the propellant until ignition occurs. The process repeats itself until the entire propellant surface in the separation groove is ignited. If a slot is provided on the nozzle end of the grain, the combustion products exhaust through the nozzle. If the main gas stream is connected by a flow channel with the propellant surface in the separation groove, side burning occurs. Side burning will not occur in Case II motors where only one slot is provided at the nozzle end, nor in Case III motors where no slots are provided.

From the film record of motor No. 9, a rate of ignition in the separation groove was calculated to be 20 in/sec. This value is 40 times higher than the normal propellant burning rate. One observing the position of the secondary peaks in the pressure-time curves for motors No. 2 and 8 shown in Fig. 9 and 10 might suspect that the ignition rates are higher for these motors. An attempt was made to correlate the position of the secondary peaks with the separation distance for these motors. Motor No. 8 had the largest separation distance, and, as expected, the peak occurred almost simultaneously with ignition. The peaks for motors 9 and 2, however, occurred in reverse positions relative to separation distances in each motor. This behavior could be caused by inaccurate measurements or, more probably, by the nonuniform separation in all motors.

Because of the short burning time of the 2-inch motors, it was decided to repeat part of this experiment using 5-inch motors. Three 5-inch motors (No. 1, 2, and 4) were fired in an effort to confirm the results obtained with the 2-inch motors. One motor each of Cases I and II was fabricated, and one motor was used as a control. Measured separation was approximately 0.065 inch in all three motors. The pressure-time traces for these firings are shown in Fig. 12. Motor No. 4, the control round, burned normally with a total burning time of 2.483 seconds. Motor No. 1 (Case I) blew up after 0.032 second. The film record for this motor showed that side burning started at the head end of the motor 0.372 second after the igniter was energized, and ignition of propellant surface in the separation groove progressed at a rate of 795 in/sec. This abnormal result is consistent with the behavior of the Case I 2-inch motors. ~~The rate of propellant ignition,~~ however, is much higher, confirming the theory that the rate of ignition

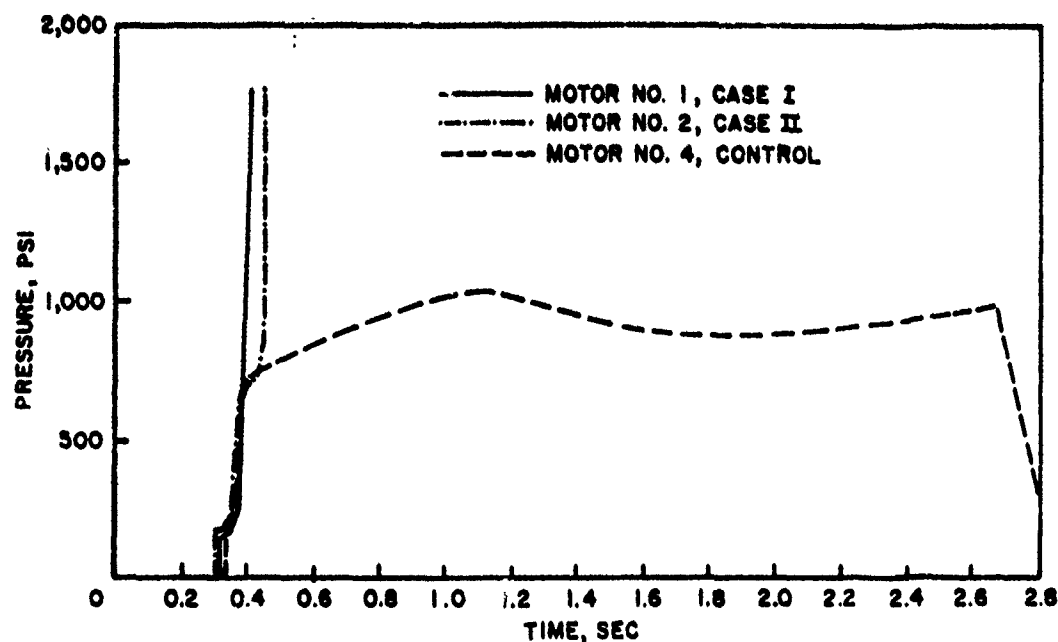


FIG. 12. Pressure-Time Curves, 5-Inch Motors No. 1, 2, and 4.

propagation depends on the width of the separation. The probability that ignition will occur depends on the existence of gas flow channels in the ends of the propellant grain.

Five-inch motor No. 2 failed after 0.109 second of operation. This result was inconsistent with the behavior of the Case II 2-inch motors. The film record, however, for this motor showed that an unexpected flow channel developed at the head end of the motor approximately 0.440 second after the igniter was energized. Thus, at this time the motor became a Case I motor rather than a Case II. The calculated ignition propagation rate was 625 in/sec. At second glance, therefore, this result is consistent with that obtained with the 2-inch motors. Figure 12 shows the pressure-time curve for motor No. 2 to be similar to that for the control round during the initial phase of burning, indicating that motor No. 2 had attained steady-state operation before failure. It is thought that this motor would have burned normally, in spite of separation, had it not been for the development of the unexpected gas flow channel at the head end of the motor.

In both cases, the motor tube unaccountably failed well below the design pressure of 4,000 psi.

CRACKED-PROPELLANT EXPERIMENT

Nine 2-inch transparent motors were fired at three different temperature levels for the purpose of studying the behavior of motors containing cracked propellant grains. Table 2 gives the design of the

TABLE 2. CRACKED-PROPELLANT EXPERIMENT
WITH 2-INCH MOTORS

Description		Firing data		
Motor No.	Width of crack in grain, in.	Temperature, °F	Ignition delay, ms	Burning time, sec
6	control motor	20	204	1.114
8	control motor	70	187	1.013
9	control motor	120	(note) ^a	(note) ^a
10	0.010	20	184	1.111
11	0.010	20	186	1.108
14	0.011	70	203	0.993
15	0.010	70	204	(note) ^a
16	0.010	120	196	0.765
17	0.009	120	865	0.863

^a Blowup.

experiment and a summary of firing data. The corresponding pressure-time curves are shown in Fig. 13, 14, and 15. Motor No. 15 at 70°F and the control motor No. 9 at 120°F blew up. Photographic coverage was lost for these two motors, and, as a result, an explanation for their unexpected failure cannot be given. Extremely high initial-pressure peaks were obtained from all motors of this test series, including the control motors. Through a mistake in processing the propellant for these motors, coated ammonium perchlorate was used instead of the uncoated material. The higher pressure exponent of this material may have caused the high initial-pressure peaks.

These data indicate that the presence of a crack in the grain does not necessarily cause failure of the 2-inch motor. In fact, with the eight-point-star internal configuration, the presence of a crack changes the burning pattern of the grain from progressive to regressive. The progressivity ratio (ratio of burning surface at web burnout to initial burning surface area) changes from 1.28 without the crack to 0.73 with the crack. This effect is reflected in the pressure-time curves shown in Fig. 13. Because the propellant has a high temperature coefficient, the amount of progressivity or regressivity in the pressure-time curves is dependent upon the temperature of the grain before testing. This is seen by comparing the curves in Fig. 13 through 15. The pressure-time curves for the 120°F firings seem to be abnormal, having rather broad initial peaks. It cannot be determined, however, whether this is the result of temperature or of a crack in the grain, since the control motor fired at this temperature blew up.

Film records of the motors containing cracked grains showed that the propellant surfaces formed by the crack ignited simultaneously with the normal burning surface.

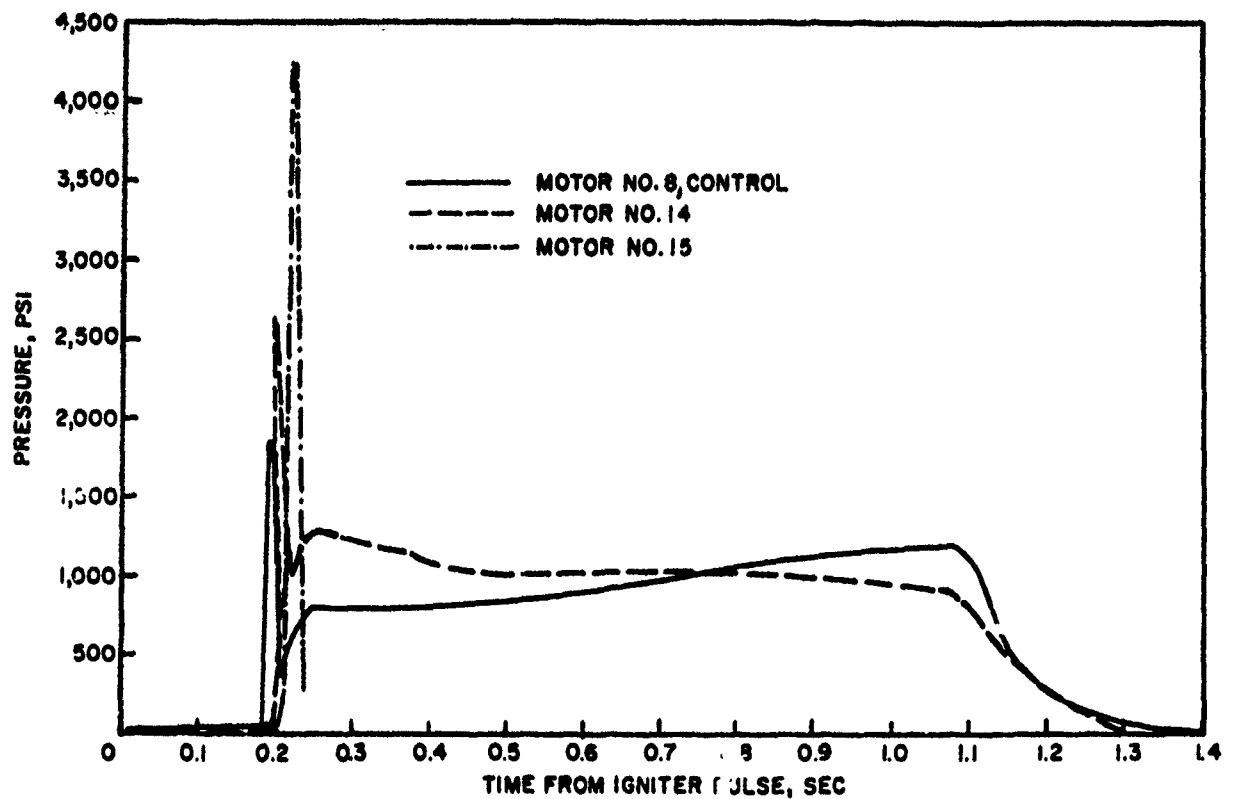


FIG. 13. Pressure-Time Curves, 2-Inch Motors No. 8, 14, and 15.

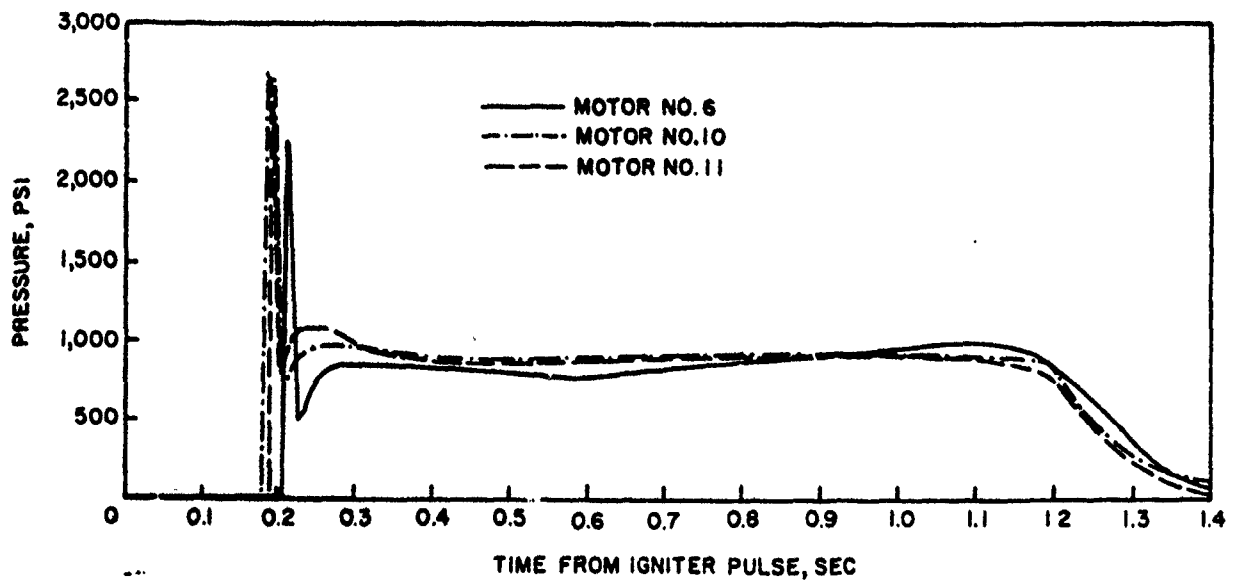


FIG. 14. Pressure-Time Curves, 2-Inch Motors No. 6, 10, and 11.

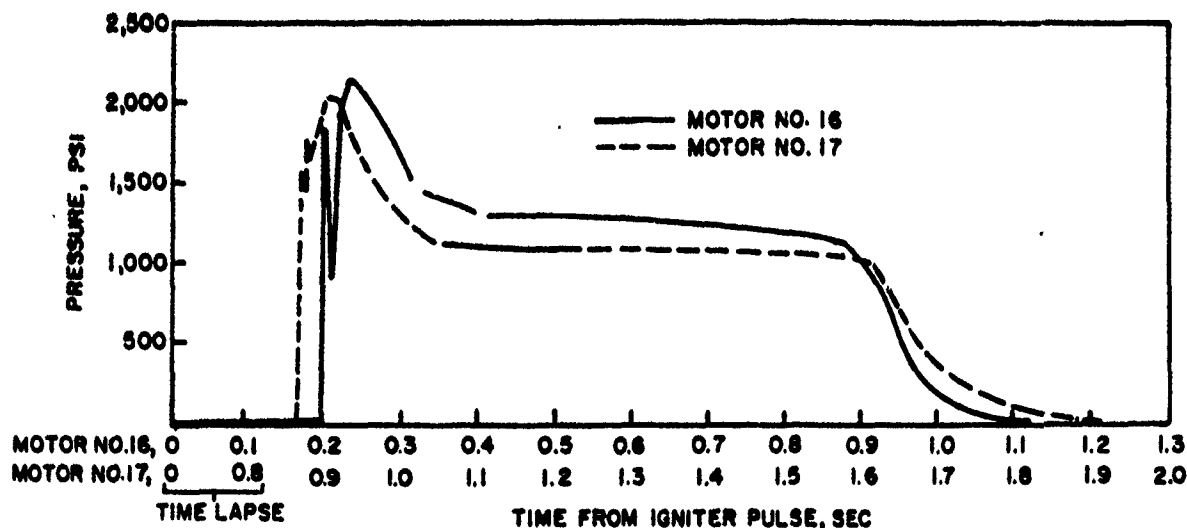


FIG. 15. Pressure-Time Curves, 2-Inch Motors No. 16 and 17.

IGNITION STUDIES

The grain configuration shown in Fig. 4 was used to study the performance of bag and hot-wire igniters. Using this arrangement, ignition of the propellant was observed and studied qualitatively. The use of a half grain permitted the observation of the igniter and the propellant surface during ignition of the motor. The motor was designed so that the ratio of the burning-surface area to nozzle-throat area was approximately the same as that for the control motor used in the liner-separation experiment. The design operating pressure was 1,000 psi. The sequence of photographs (Fig. 16) shows various stages of the ignition of a propellant grain, using bag igniter. The pictures show that the flame pattern within the cavity is not symmetrical, and approximately all of the propellant surface is ignited before hot gases can be seen emerging from the nozzle. BCT data indicated that 176 milliseconds were required for the igniter to respond to the initial input of current and begin to burn. This interval is sometimes referred to as igniter delay. A total of 55 milliseconds was required for the entire propellant surface to ignite after the initial igniter response. Pressure data were lost during this test, and therefore picture sequences could not be correlated with motor pressure.

A hot-wire igniter was also studied. This igniter consists of a helix of high-resistance Nichrome wire, 0.010 inch in diameter, inserted into the cavity of the motor so that it is in contact with the propellant. The igniter is actuated by a current of 18 amperes. In contrast with the bag type, this igniter gave a long ignition delay. Ignition of the propellant proceeded as follows: The igniter responded as indicated by a red glow emitted by the hot wire 0.654 second after the current was applied. The whole length of wire began to glow after 0.721 second. The wire appeared to break up, and the propellant smoldered, but no aluminum

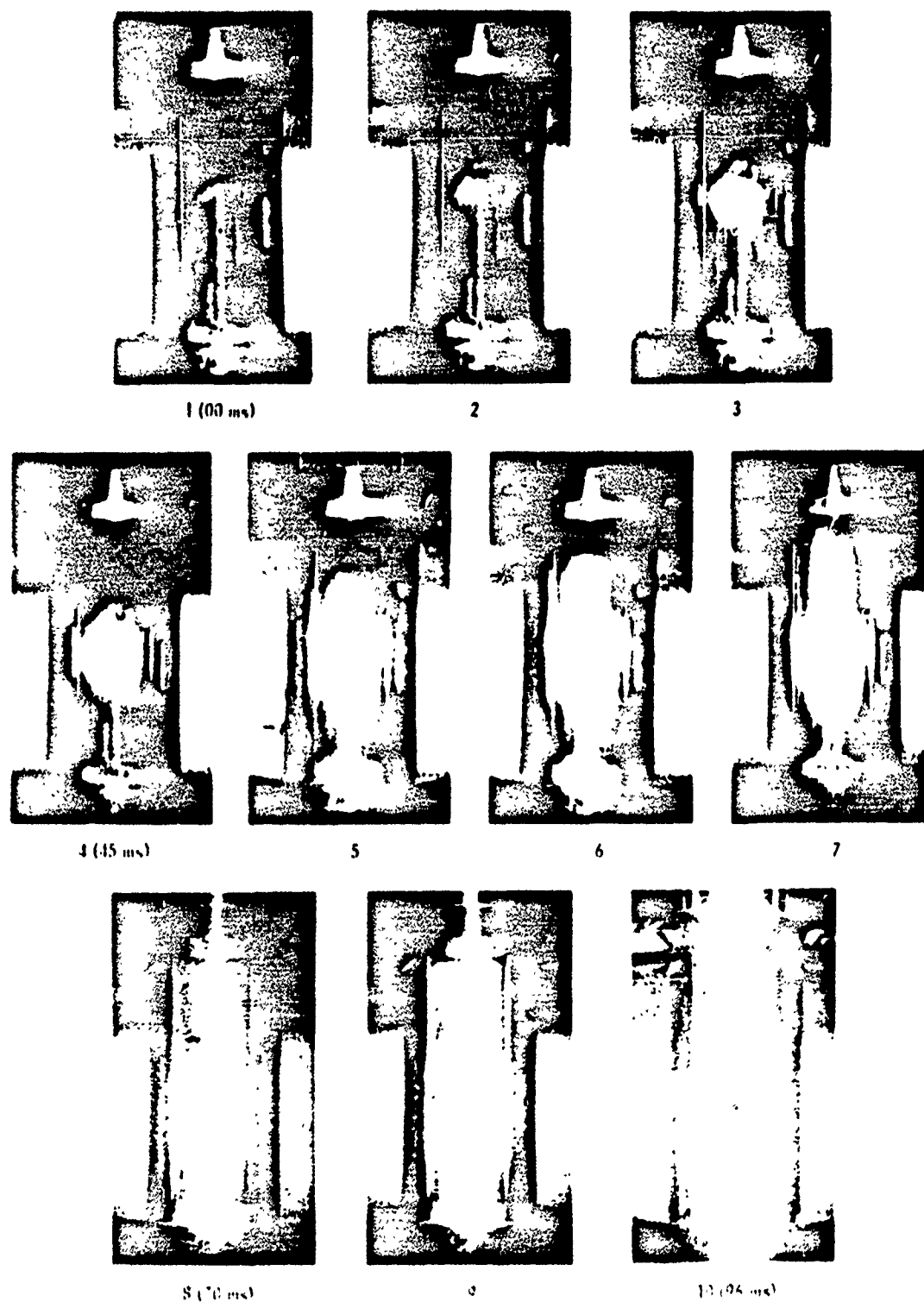


FIG. 16. Ignition of Half-Motor.

burned after 1.176 seconds. The entire propellant surface smoldered with little burning of aluminum inside the motor at 4.459 seconds. The entire surface of the propellant appeared to burn with combustion of aluminum at 4.759 seconds. The motor pressure at this time was 52 psi. The motor reached 250 psi at 4.804 seconds. This motor failed after 0.109 second of operation at a pressure of 1,930 psi. An examination showed that the propellant surface was irregular with equally spaced depressions. It is concluded that these depressions occurred at points of propellant contact with the coils of the wire igniter. The propellant first ignited at these points. This experiment showed the difference in ignition characteristics between the bag and hot-wire igniters.

HOT-SPOT FORMATION

Film records of the majority of motor firings showed the formation of hot spots at the liner-propellant interface a long time before web burnout. In several motors, burning at the case wall occurred halfway through the burning period. Burning at the wall usually appeared as a small, circular area that grew larger as burning progressed. It has been shown by other workers that this phenomenon is caused by small, spherical voids present in the propellant.³ When burning within the void occurs, the pressure is higher than the average motor pressure. Thus, the burning rate of the propellant in the void is greater than in the chamber. Pressure records show, however, that the existence of hot-spot burning does not alter the ballistic performance of the motor even though the defect propagation is greater than the regression of the normal burning surface.

SUMMARY AND CONCLUSIONS

Studies of burning characteristics associated with grain defects were made by photographically viewing reactions through the walls of transparent motor tubes. Associated instrumentation, such as BCT, allowed accurate correlation of ballistic and photographic data. Such phenomena as flame propagation through a crack, side burning, and hot-spot formation were observed directly.

The existence of liner-propellant separation alone did not appear to alter ballistic performance. When this condition was present, together with flow channels at each end of the motor, severe alterations of the pressure-time curves occurred, in some cases causing catastrophic

³ Allegreto, D. P., and D. B. Painter, "Photographic Studies of the Effect of Grain Defects on Burning Characteristics of Highly Aluminized Composite Solid Propellant," Bulletin of the 16th Meeting of the Joint Army-Navy-Air Force Solid Propellant Group, Vol. V (1960), pp. 181-195, CONFIDENTIAL.

failure of the motor. Flame propagation in the separation occurs as a result of an ignition wave, which may travel at a rate of 765 in/sec, depending on the width of the separation groove. It is not known at this time whether this ignition wave is preceded by a shock wave.

These studies have shown that the existence of a crack flaw appears to be less detrimental to normal motor performance over a wide temperature range. High ignition peaks, however, are associated with this type of flaw and probably could cause motor failure under certain conditions. If the motor survives the initial peak pressure, and if the crack extends from the port to the wall, the instantaneous flame progression to the motor case wall will always occur. In a large motor, severe heating of the motor case and its subsequent rupture could be the result.

The possibility of hot-spot formation is ever present during motor operation. While it was found not to affect the ballistics of the motor, hot-spot formation can cause severe heating of the motor case. This behavior is thought to be the result of small voids in the propellant, which can be detected by radiographic techniques.

The ignition of a propellant surface depends to a great extent on how the heat is transferred to the propellant surface. The transparent half-motor appears to be a useful tool for evaluating the performance of igniters and for studying the response of a propellant surface to ignition energy under conditions similar to those found in practical rocket motors.

It is hoped that the information presented in this report will aid in providing a more accurate basis for the acceptance or rejection of a rocket motor.

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